INDUCTION CELL BREAKDOWN EXPERIMENTS FOR THE DUAL-AXIS RADIOGRAPHIC HYDROTEST (DARHT) FACILITY

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Abstract

Linear induction cells for the Dual-Axis Radiographic Hydrotest (DARHT) Facility have been tested to determine their high-voltage breakdown characteristics. A variety of full scale insulators were tested both in actual cells and in fixtures simulating induction cells. All insulators were constructed using cross-linked polystyrene (Rexolite). High-voltage pulses up to 550 kV were applied to the insulators using both a 60-ns pulse Blumlein and a 200-ns pulse cable Marx. Two different vacuum gaps were used in these tests, 1.46 and 1.91 cm. The tests were performed at various vacuum levels ranging from 1×10^{-6} to 5×10^{-8} torr. Breakdown tests of the insulators were also performed with an electron beam generated in the vacuum gap through the use of a velvet emitter. The gap voltage and current were measured using calibrated E-dot and B-dot probes.

Introduction

The DARHT facility at Los Alamos will generate intense bremsstrahlung x-ray pulses for radiography using two linear induction accelerators (LIA). Each LIA will produce a 3-kA, 16- to 20-MeV, 60-ns flattop, high-brightness electron beam using a 4-MeV injector and a series of 250-kV induction cells. Each cell consists of an oil-insulated ferrite core, an accelerating gap with carefully profiled electrodes and insulator, and a solenoid magnet to transport the electron beam. This paper summarizes the high-voltage testing of the various gap and insulator designs for the LIA cell.

The cell development process included the design, fabrication and testing of three prototype cell configurations. In chronological order, these are referred to as Mod 0, Mod 1, and Mod 2 and are shown in Fig. 1. The complete DARHT cell design characteristics are given by Burns, et. al. [1]. The cell design process included evaluation of the LIAs constructed at Lawrence Livermore National Laboratory. Table I gives a summary of the vacuum gap dimensions and insulator types for three cell designs, 1) ATA, Advanced Test Accelerator [2,3,4], 2) FXR, Flash X-ray Machine [5], and 3) ETA-II, Experimental Test Accelerator II [6].

Table I

Cell Type	Vacuum Gap(cm)	Insulator	Gap Voltage(kV)
ATA	2.54	Ceramic	250
FXR	3.81	Epoxy	300-400
ETA-II	0.75	Ceramic	100-125
MOD 0	1.46	Rexolite	250
MOD 1	1.46	Rexolite	250
MOD 2	1.91	Rexolite	250

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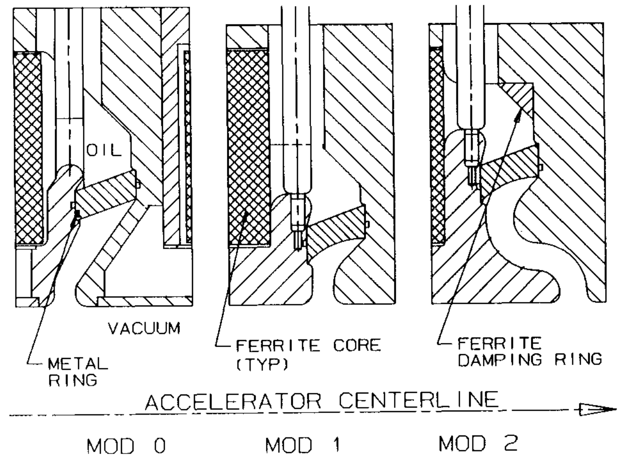

Fig. 1. Accelerating gap region of the three prototype DARHT cell designs.

Since the DARHT injector uses a velvet-based cold cathode, plastic cell insulators were an option. Rexolite was chosen over Lucite due to its superior mechanical properties. An extensive body of literature exists for breakdown data of insulators but little data are available for short pulses with Rexolite. The classic insulator breakdown papers [7-10] contain standard design guides for vacuum gaps as well as experimental data for many insulator materials. The present investigation combines the standard design guides together with computer modeling of the cell using the two-dimensional finite-element codes FLUX2D [11] and POISSON.

In the normal operation of the DARHT cell, the equivalent cell load impedance to the pulse power drive is matched, resulting in a gap voltage which is only a single polarity. A bipolar gap voltage can result from a mismatch between the pulsed power and the cell load if the voltage is applied to the gap when no beam is present. In DARHT, the cell vacuum gap and insulator were conservatively designed for the worst case of bipolar gap voltage. Thus, a uniform field distribution was selected. However, a uniform field distribution across the cell insulator is not the best design [12] for unipolar stress.

We limited the peak design electric field stress to 200 kV/cm for the type 304 stainless steel electrodes that form the accelerating gap for an applied voltage of 250 kV. The vacuum gap in both the Mod 0 and Mod 1 designs is 1.46 cm while the Mod 2 design uses a 1.91 cm gap. In all three cell designs, the vacuum gap was enlarged in the area of the insulator to 4.0 cm. The Mod 2 design uses a more complicated geometry which shields the insulator from the electron beam, while reducing the

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14. ABSTRACT
Linear induction cells for the Dual-Axis Radiographic Hydrotest (DARHT) Facility have been tested to determine their high-voltage breakdown characteristics. A variety of full scale insulators were tested both in actual cells and in fixtures simulating induction cells. All insulators were constructed using cross-1 inked polystyrene (Rexol ite). High-voltage pulses up to 550 kV were applied to the insulators using both a 60-ns pulse Blumlein and a 200-ns pulse cable Marx. Two different vacuum gaps were used in these tests, 1. 46 and 1.91 em. The tests were performed at various vacuum levels ranging from 1 x 10"6 to 5 x 10"8 torr. Breakdown tests of the insulators were also performed with an electron beam generated in the vacuum gap through the use of a velvet emitter. The gap voltage and current were measured using calibrated E-dot and B-dot probes.

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transverse impedance of the cell. The vacuum gap in the DARHT cell was designed much smaller than either the ATA or FXR gaps in order to reduce the transverse impedance of the cell to the beam. The final gap dimensions were determined with the AMOS code [13] which is a two-dimensional finite-difference, time-domain, electromagnetic simulation code. Large cell transverse impedances can lead to beam breakup (BBU) in LIAs [14].

Mod 0 Experiments

Testing of the Mod 0 insulator was performed with a modified ETA-II [15] Blumlein. The line length was doubled to provide a 60-ns flattop output pulse. The Blumlein output was connected to four 44-Ω solid-dielectric output cables (Dielectric Sciences DS2077) in parallel, which in turn drove two identical cells in parallel. The Blumlein output pulse has a nominal 25-ns risetime. The output peak voltage could be continuously adjusted from -70 kV to -250 kV. Each cable feed into the cell was terminated in a parallel load consisting of a 54-Ω compensation resistor, the ferrite load impedance, and the gap capacitance of approximately 100 pF. The equivalent load impedance for the output cable was close to a matched load. The actual gap voltage in the cell was monitored with four E-dot probes mounted every 90° around the circumference of the cell directly in the vacuum gap. Figure 2 shows the measured vacuum gap voltage with -250 kV applied. The voltage was taken from the summation of the four E-dot probes and then passively integrated with a 50-Ω integrator with a bandwidth greater than 500 MHz. The signal was recorded with a Tektronix 7103 scope equipped with the Tektronix digital camera system (DCS). All waveforms were recorded to disk using a PC controller for the DCS.

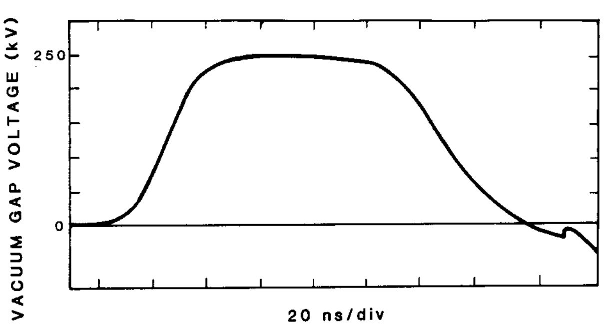

Fig. 2. Vacuum gap voltage pulse.

The cell was pulsed for approximately 800 shots for voltages below -250 kV and an additional 600 shots at -250 kV. No gap breakdowns were observed. Since the maximum operating voltage of the Blumlein was -250 kV, the cell compensation resistors were changed to 130 Ω each to step up the gap voltage using a mismatched load on the output of the Blumlein. The output voltage was raised in 15 kV steps to determine the cell breakdown voltage. Twenty shots were taken at each voltage level. Breakdown of the gap occurred on the ninth shot at -350 kV. The vacuum level was maintained constant during these tests at 2×10^{-7} torr. Figure 3 shows the gap voltage waveform for this breakdown.

Mod 1 Experiments

The Mod 1 insulator was tested in a fixture which was designed to simulate the actual induction cell geometry. The main differences were that neither ferrites nor compensation resistors were present. Only the vacuum gap with the oil reservoir surrounding the insulator exterior was used. The fixture and the insulator were full scale to simulate all area effects in the experiment. Figure 4 is a cross-sectional view of the experiment. An open-air cable Marx generator manufactured by Field Emission Corp. was used to apply a 200-ns wide pulse to the vacuum gap. The charge cables for the Marx were RG19. The output pulse had a risetime of 50 ns and could be continuously adjusted from -130 kV to -550 kV. The output impedance of the Marx was approximately 275 Ω. In order to provide some stabilization to the load, an open-air series stack of four 70-Ω carborundum resistors was used. Figure 5 is a schematic of the experimental setup. A 0.1-Ω current viewing resistor (CVR) was used to measure the current flowing through the stabilizing load. The capacitance of the chamber was calculated to be 200 pF. A large copper ground plane was used for the cable Marx, load resistor and the insulator test chamber. The cables connecting the Marx to the resistor and chamber were RG220 with the outer conductor removed. The chamber diagnostics included an E-dot in the main gap, an E-dot oriented to look at the side of the high-voltage electrode, a B-dot oriented to measure currents crossing the gap, and a Pearson coil measuring the return current from the chamber to the ground plane. The vacuum level for these tests was 1×10^{-7} torr.

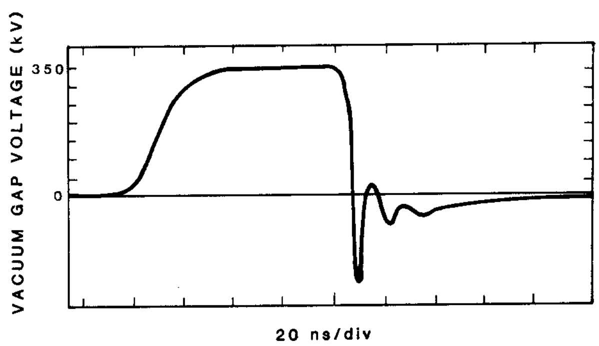

Fig. 3. Vacuum gap voltage breakdown for applied pulse of -350 kV.

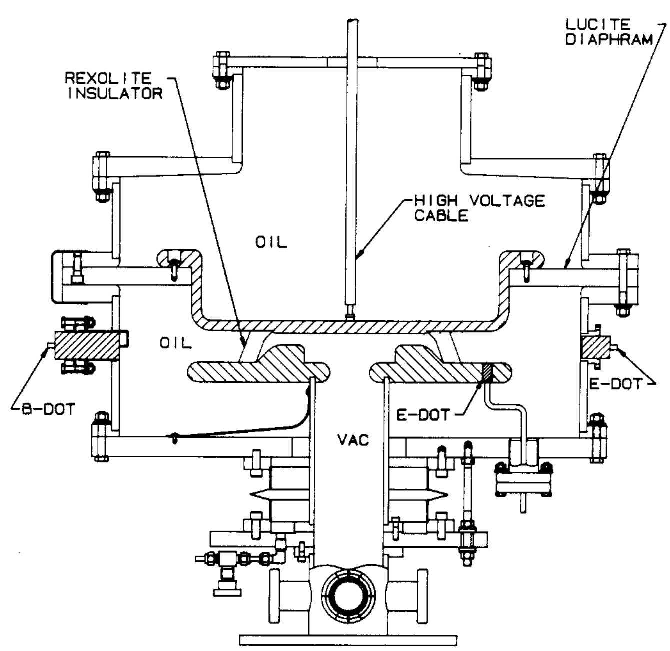

Fig. 4. Cross-sectional view of the Mod 1 insulator test chamber.

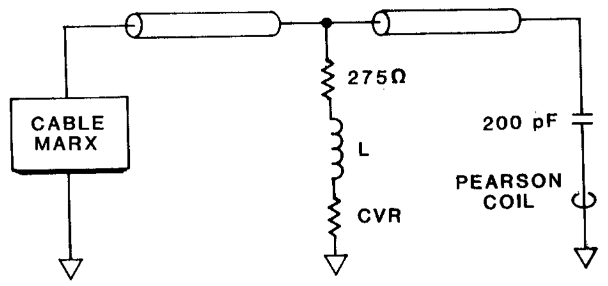

Fig. 5. Schematic diagram of the Mod 1 experiment.

Figure 6 shows the gap voltage measured with the E-dot in the vacuum gap. The signal was passively integrated and recorded with a Tektronix 7104 scope with DCS. The waveform was software corrected for integrator droop. The cable Marx was operated at rate of 6 shots per minute. The tests started with a gap voltage of -130 kV, which was raised in steps of 20 kV with 100 shots taken at each step up to -300 kV. One thousand shots were taken at a gap voltage of -300 kV. The steps were changed to 10 kV with one thousand shots taken at each step to - 350 kV. Ten thousand shots were taken at -350 kV. One thousand shots were again taken in 10 kV steps to -400 kV. Only minor conditioning breakdowns were occasionally observed. These conditioning pulses did not leave physical damage. Above -400 kV the steps were changed to 5 kV with 50 shots at each step. The test was terminated at -500 kV.

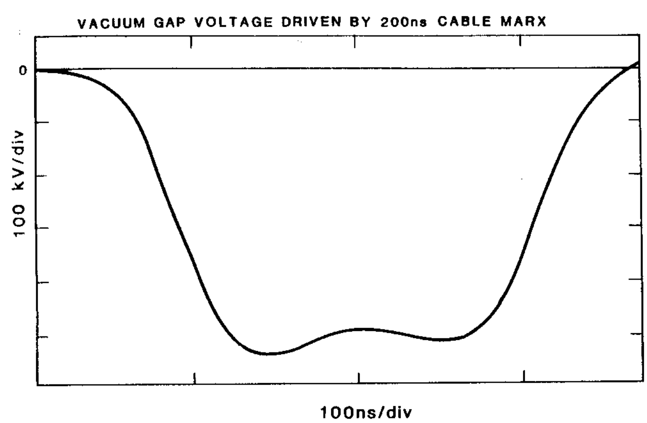

Fig. 6. Mod 1 vacuum gap voltage pulse.

The tests were repeated with the applied voltage polarity changed to positive. The test was started with the gap voltage at +130 kV and increased in 20-kV steps to +350 kV. One hundred shots were taken at each voltage. Voltage breakdown occurred on the first shot at +350 kV.

Breakdown tests were also performed with an electron beam generated in the vacuum gap through the use of a velvet emitter. The test was an attempt to simulate the actual accelerator cell operation with large beam spill present. No guiding magnetic field was used for this test. The intent was for the electron beam to create as much ultra-violet radiation as possible which would enhance the breakdown of the insulator. A velvet circular flat cathode of area 1 cm^2 was placed on the negative electrode in the region where the vacuum gap was smallest. The voltage across the gap was varied from -150 kV to -300 kV in 30 kV steps. One hundred shots were taken at each step. The experiment was repeated several times in order to check for reproducibility of the data. Each time the current increased as calculated from space charge limited flow up to a gap voltage of 270 kV. At 300 kV the beam turned into an arc across the vacuum gap to the velvet. The emitter current was measured each pulse using both the B-dot probe and the Pearson coil. To determine the emitter current, the experiment was repeated at the same voltages without the velvet present. The current probes measure the charging and discharging of the gap capacitance as well as any beam or arc current. Thus, to determine the beam current only, one had to subtract the current waveforms without velvet from the current waveforms with velvet. In this way the gap charging current could be removed. This was accomplished by using the waveform subtraction feature in the DCS software. Figure 7 shows a plot of the beam current versus gap voltage. A curve fit of Child-Langmuir flow is also plotted with the measured data points. Several hundred amperes of current were emitted from the velvet. No insulator damage was found after a gap breakdown.

Mod 2 Experiments

Figure 7 shows a cross sectional view of the Mod 2 experiment. The test chamber exterior was the same as for Mod 1, however, both the insulator and the electrodes were changed. The diagnostic setup had one change from Mod 1. The gap E-dot probe was moved to the vacuum side of the insulator rather than the oil side as in Mod 1. The electrical setup shown in Fig. 5 was identical for Mod 2 as was Mod 1.

The Mod 2 insulator program included only negative polarity tests at this time. The test was started at -130 kV and increased in 20-kV steps with one hundred shots at each step. Voltage breakdown was recorded at -520 kV. The breakdown would repeat even after reducing the voltage to -400 kV. Examination of the insulator and gap indicated that breakdown occurred in the gap at the location of the E-dot probe. The edge of the probe showed several arc spots. The aperture in the electrode holding the E-dot was enough of a perturbation to the local fields that breakdown was preferential to the aperture rim.

The Mod 2 testing was repeated at two different vacuum levels. The first was 5 x 10^{-8} torr and the second was 1 x 10^{-6} torr. Breakdown occurred for the better vacuum at -520 kV and -480 kV for the poorer vacuum.

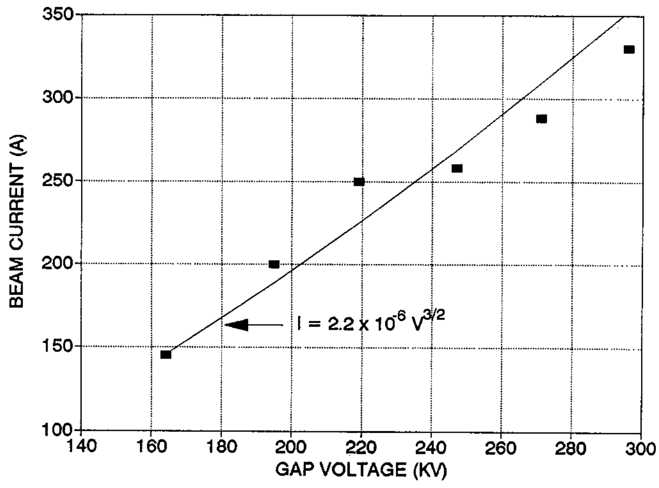

Fig. 7. Beam current vs vacuum gap voltage.

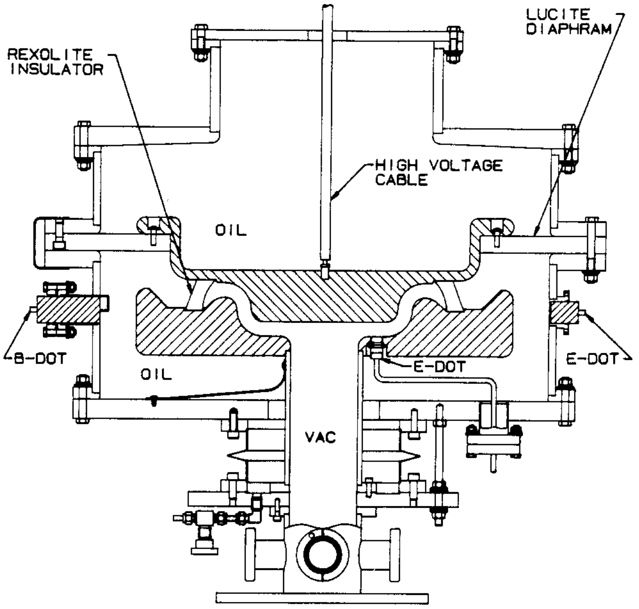

Fig. 8. Cross-sectional view of the Mod 2 insulator test chamber.

Summary

Three cell designs for the DARHT LIA have been extensively tested with tens of thousands of high voltage pulses. Results from the Mod 1 and Mod 2 cells indicate that the high-voltage design of the cells is conservative. An earlier design, Mod 0, also has measured performance which is more than adequate. The cell design was optimized for bipolar high-voltage operation, which again is conservative. Due to the programmatic requirements of high reliability for the DARHT LIA, conservative pulsed power practices are a necessity.

Since the results with the cable Marx pulser gave higher breakdown values than the Blumlein pulser, one must examine the effects of conditioning with a high-impedance source such as the cable Marx. At the present time one cannot determine whether the Mod 1 or Mod 2 cell will operate at voltages above 350 kV when driven with a low-impedance source such as a Blumlein. However, normal operation of the cells will be at 250 kV. An eight cell assembly using the Mod 2 cell design driven by four Blumleins will be operational at the DARHT Integrated Test Stand in the near future.

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